COFRDA REPORT 3316

Hydrology of Drained and Undrained Black Spruce Peatlands: Surface Water and Groundwater Quality

Forest Resource Development Agreement
Entente sur la mise en valeur de la ressource forestière

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Hydrology of Drained and Undrained Black Spruce Peatlands: Surface Water and Groundwater Quality

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ABSTRACT

Surface water and groundwater quality were examined in drained and undrained black spruce (*Picea mariana* [Mill.] B.S.P.) peatlands. In surface water, drainage caused increases in concentrations of all major ions, of some heavy metals (Al, Fe, Cu and Mn), of NH_4^+–N and in total P; and in pH, alkalinity, conductivity, suspended solids and temperature. For most measures, guidelines for freshwater aquatic life were seldom or never exceeded. However, the high natural concentrations of Al, Cu and Fe exceeded these guidelines for waters from both drained and undrained areas. For Operational Group 11, groundwater in drained plots had higher concentrations of most major ions; of the metals Al, Fe and Mn; of (NO_2^- + NO_3^-)–N, total Kjeldahl N and total P; and of pH and conductivity. The higher values are mostly explained by increased decomposition of peat resulting from increased aeration. Only K^+ decreased in drained Operational Group 11 plots, and several metals or ions (Cu, Hg, Pb, Zn and NH_4^+–N) showed no change. For Operational Groups 12 and 14, sample variability was too large and results too mixed for consistant predictions.

RÉSUMÉ

On a examiné la qualité de l'eau de surface et de l'eau souterraine de tourbières d'épinette noire (*Picea mariana* [Mill.] B.S.P.) drainées et non drainées. Dans l'eau de surface, le drainage entraînait une augmentation des concentrations de tous les principaux ions, de certains métaux lourds (Al, Fe, Cu et Mn), de NH_4^+–N, de P total, du pH, de l'alcalinité, de la conductivité, des matières solides en suspension et de la température. Dans la plupart des cas, les valeurs précisées par les directives pour la vie aquatique en eau douce n'ont été que rarement ou jamais dépassées. Cependant, les fortes concentrations naturelles de Al, Cu et Fe dépassaient ces valeurs dans l'eau aussi bien des zones drainées que non drainées. Chez le Groupe opérationnel 11, l'eau souterraine des parcelles drainées renfermait des concentrations plus élevées de la plupart des principaux ions: métaux Al, Fe et Mn; (NO_2^- + NO_3^-)–N, N total de

Kjeldahl et P total; pH et conductivité. Les valeurs plus fortes s'expliquent dans la plupart des cas par la plus fortedécomposition de tourbe résultant de l'aération plus intense. Seul K^+ a diminué dans les parcelles drainées du Groupe opérationnel 11, et plusieurs métaux ou ions n'ont accusé aucune variation (Cu, Hg, Pb, Zn et NH_4^+–N). Dans le cas des groupes opérationnels 12 et 14, la variabilité des échantillons était trop importante, avec des résultats trop disparates pour permettre des prévisions cohérentes.

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HYDROLOGY OF DRAINED AND UNDRAINED BLACK SPRUCE PEATLANDS: SURFACE WATER AND GROUNDWATER QUALITY

INTRODUCTION

In Ontario, more than 8 million hectares of productive black spruce (*Picea mariana* [Mill.] B.S.P.) forest have been estimated to occur on peatland (Ketcheson and Jeglum 1972). Forest drainage has been shown to increase tree growth by lowering the groundwater table (Payandeh 1973, Stanek 1977, Heikurainen and Joensuu 1981, Dang and Lieffers 1989). Improved growth is the silvicultural result of drainage. There is also an environmental impact aspect that is concerned with such factors as changes in vegetation (Heikurainen and Pakarinen 1982) and changes in water quality. The quality of surface water—in this study, that of the drainage ditches and streams—influences stream beds and aquatic ecosystems. Groundwater quality is of interest because it affects both on-site vegetation and, when it flows into ditches and streams, the quality of the surface water. A question that results from this impact perspective must be answered: Does drainage degrade surface water or groundwater quality?

Peatlands are inherently complex and diverse ecosystems, and they vary in surface water and groundwater quality (Clausen et al. 1980). The effects that drainage has on water quality depend in turn on the soil parent material, peatland type, plant species and climate (Boelter and Verry 1977). Hence, the effects of drainage will vary between basins that differ in these criteria. Some common previously reported effects on surface water quality are increased concentrations of suspended solids, as well as increased pH and alkalinity (Heikurainen et al. 1978, Seuna 1982, Hynninen and Sepponen 1983, Ahtiainen 1988, Lundin 1988); however, drainage effects are not always consistent. For example, total N has been reported to increase in some studies and to decrease in others, and concentrations of cations have increased or shown no change (Hynninen and Sepponen 1983, Ahtiainen 1988, Lundin 1988). The effects of peatland drainage on surface water quality are attributed to increased aeration of the peat, which allows aerobic mineralization processes to occur. Percolating water passing through the upper peat horizons during storm events transports the products of mineralization into the surface water (Lundin 1987).

The wide range of reported results indicates that the development guidelines for drainage require research into the ecological changes that drainage can cause in peat environments. Drainage of forested peatlands to improve tree growth is being investigated in several regions of Canada (Hillman 1987). A project was initiated in 1984 by the Ontario Ministry of Natural Resources in cooperation with Forestry Canada's Ontario Region to study forest drainage and produce the necessary management guidelines (Koivisto 1985, Rosen 1986a, Jeglum 1991). The present paper is one of a series dealing with the hydrological impacts of drainage at the Wally Creek Area Forest Drainage Project. Two papers have dealt with groundwater table profiles and fluctuations (Berry and Jeglum 1988, 1991), two with water quality (Berry 1991a and the present paper), and one with streamflow (Berry 1991b).

The objective of this study was to characterize the influence that drainage has on the surface water and groundwater quality of forested swamps of the main peatland site types of the Forest Ecosystem Classification (Jones et al. 1983). These site types, termed Operational Groups (OGs), are defined as landscape segments with mature forest that have an identified range of vegetation and soil conditions and probable

responses to specific management prescriptions. In this study, the term "groundwater" refers to water under both saturated and unsaturated soil moisture conditions.

STUDY AREA

The Wally Creek Area Forest Drainage Project is located 30 km east of Cochrane, Ontario (49°3' N, 80°40' W), in the Northern Clay Section of the Boreal Forest (Rowe 1972). Climatic data for Cochrane (Anon. 1982a,b,c) indicate that the area has a continental climate, with cold winters and warm, moist summers. The mean annual temperature is 2°C, with monthly means averaging between -18°C (January) and 17°C (July) and extremes of -45°C and 38°C. Approximately 66% of the total annual precipitation of 885 mm occurs as rain. More than 42% of the total (378 mm) occurs as rain from June through September. The remainder is evenly distributed throughout the other months. There is an average of 1328 degree-days (>5°C) per year and potential evapotranspiration (Thornthwaite's method) is estimated to be 490 mm/year (Anon. 1985).

The flat topography of the Wally Creek area, which generally has a slope of <0.3%, has a natural drainage toward the northwest. The peat in the study area is of variable depth (<30 to >300 cm) and overlies a heavy clay of lacustrine origin. The area is forested with uneven-aged (50 to 140 years, 8 to 17 m tall) black spruce (*Picea mariana* [Mill.] B.S.P.); it has been site-typed in accordance with the Forest Ecosystem Classification (Jones et al. 1983). The vegetation of the three main peatland types is described in Table 1.

METHODS

Drainage Prescription

Ditches in the ca. 450 ha area north of the highway (Fig. 1) were planned and installed in

Table 1. Description of vegetational characteristics of operational groups (OGs).

OG	Canopy	Shrub layer[a]	Moss layer[a]
11	black spruce	*Ledum groenlandicum* *Vaccinium myrtilloides* *Chamaedaphne calyculata*	*Sphagnum nemoreum* *S. fuscum* *S. magellanicum* *S. girgensohnii* *Pleurozium schreberi* *Ptilium crista-castrensis*
12	black spruce	*Alnus rugosa* *Vaccinium myrtilloides* *Ledum groenlandicum* *Chamaedaphne calyculata*	*Sphagnum magellanicum* *S. nemoreum* *S. girgensohnii* *Pleurozium schreberi* *Ptilium crista-castrensis*
14	black spruce	*Chamaedaphne calyculata* *Ledum groenlandicum* *Kalmia polifolia*	*Sphagnum fuscum* *S. angustifolium* *S. wulfianum* *S. magellanicum*

[a] Listed in order of decreasing frequency in the OG.

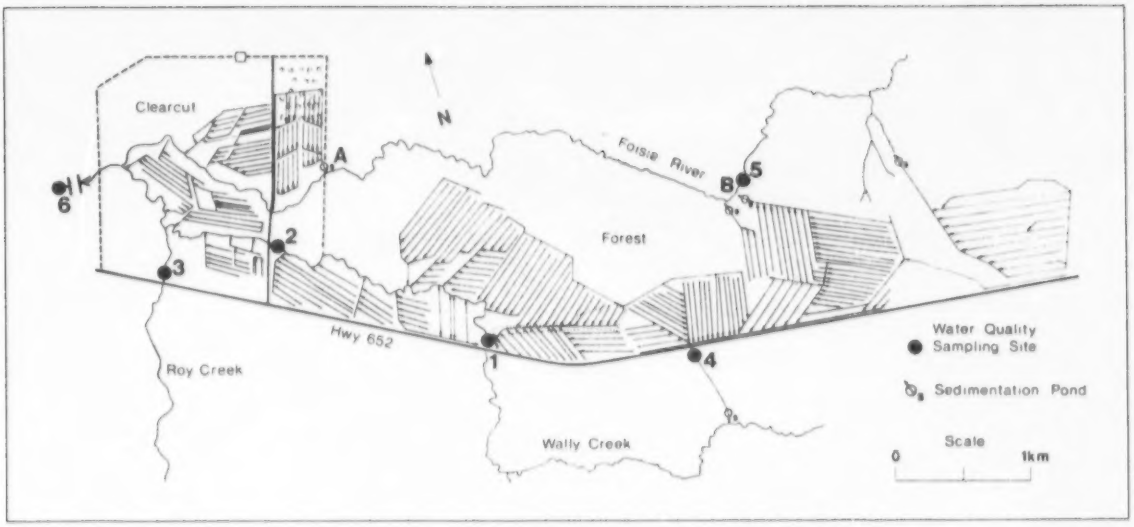

Figure 1. Map of the Wally Creek Project drainage network, showing water-quality sampling sites (1-6) and sedimentation ponds (A, B).

1984 to Finnish standards, through the services of an experienced Finnish consultant and machine operators (Koivisto 1985, Rosen 1986b). Spacing of ditches was based on Finnish guidelines for sites equivalent to the OGs. The recommended spacings were from 30 to 50 m, spacings intended to give an average water-table depth of from 40 to 45 cm across the between-ditch strip. The actual spacing between the ditches was varied from 19 to 75 m in order to verify the applicability of the Finnish recommendations to northern Ontario site and climatic conditions. Almost 72 km of ditches were installed over 280 ha, giving a mean ditch density of 254 m/ha. In most of the area, side ditches averaged 90 cm in depth; collector and surround ditches averaged 120 cm in depth. In 1985, an additional 170-ha area was harvested by clearcutting and 59 ha were drained. In total, 339 ha were drained.

Water Sample Collection and Analysis

Surface water

"Grab" samples were taken at mid-channel, through the entire depth (i.e., depth-integrated sampling) at eight locations (Table 2, Fig. 1). The sites were located:

- in Wally Creek upstream and downstream of collector-ditch outlets (sites 1 and 2)
- in Roy Creek, upstream of any drainage (site 3)
- in a collector ditch (site 4)
- in the Foisie River, upstream of most of the drainage network (site 5) and ca. 2.5 km downstream of the entire network (site 6)
- around sedimentation ponds (ponds A and B)

Sites were classified as controls (sites 1 and 3), treatments (sites 2, 4 and 6) or as a sub-treatment (site 5). Site 5 could not be termed a control because of the influence of the drainage ditches upstream of this site. However, it was used as a comparison for treatment site 6. Although the collector ditch from site 4 emptied into Wally Creek upstream of site 1, the effects were assumed to be minimal because of the much greater flows in Wally Creek, as indicated by the relative basin areas (Table 2). All the basins comprised a mixture of different OGs; there were no basins comprising only one OG.

Samples from sites 1 to 6 underwent the chemical and physical analyses outlined in

Table 2. Description of surface-water sample collection locations.

Site	Description	Basin area (ha)	Drained area (ha)	% Drained	Notes
1	Wally Cr. - upstream of drainage	1297	-	-	Control
2	Wally Cr. - downstream of drainage	1499	139	9	Treatment - lightly drained small basin
3	Roy Cr. - upstream of drainage	466	-	-	Control
4	Collector Ditch - downstream of drainage	67	58	87	Treatment - heavily drained
5	Foisie R. - upstream of drainage	766	68	9	Sub-treatment
6	Foisie R. - downstream of drainage	4768	341	7	Treatment - lightly drained large basin
	Sedimentation Pond A	-	7	-	-
	Sedimentation Pond B	-	43	-	-

Table 3. Samples at each of the two sedimentation ponds were obtained from the ditch leading into and out of the pond, as well as upstream and downstream of the pond outlet into the river channel. These sets of samples were analyzed for suspended solids only, and were used to determine the effectiveness of the ponds in removing sediment.

Water samples were collected in 1987, 1988 and 1989, beginning before snowmelt and ending just before the onset of freeze-up. Collections were made, on average, every 10 days in 1987 and every 6 days in 1988 and 1989. Periodic collections were made around storm events to determine the effect of periods of high flow on water quality. This collection schedule permitted a wide variety of flow conditions to be sampled. An exception to this schedule was the sampling for mercury (Hg). Samples for this analysis were collected only in 1989, during low-flow conditions in July and high-flow conditions in September.

Table 3. Chemical and physical analyses.

Major ions Ca^{2+}, K^+, Mg^{2+}, Na^+, Cl^-, SO_4^{2-}, SiO_2
Nitrogen (N) and Phosphorus (P) TKN (total Kjeldahl N), NH_4^+–N, (NO_2^-+NO_3^-)–N, TP (total P)
Metals Al, Cd, Cu, Fe, Hg, Ni, Mn, Pb, Zn
Other analyses pH, alkalinity, conductivity, suspended solids, temperature

Suspended solids were analyzed gravimetrically using 1.4-µm filters. Electrical conductance, pH and alkalinity were measured with standard equipment and methods (Anon. 1981b).

Surface waters were filtered (0.45-µm pore size) before chemical analysis. Cations were analyzed with an atomic absorption spectrophotometer by flame-emission spectrophotometry for potassium (K^+) and sodium (Na^+) and by atomic-absorption spectrophotometry for calcium (Ca^{2+}) and magnesium (Mg^{2+}). Sulphate (SO_4^{2-}), chloride (Cl^-), nitrite plus nitrate nitrogen ([NO_2^- + NO_3^-]–N), ammonium nitrogen (NH_4^+–N) and silica oxide (SiO_2) were measured with a Technicon Autoanalyzer II system by the methylthymol blue, mercuric thiocyanate, cadmium reduction, sodium nitroprusside, and ascorbic acid methods, respectively. In highly

colored samples, SO_4^{2-} and Cl^- were measured by means of ion chromatography. Metals were analyzed in a graphite furnace using atomic-absorption measurements; these included aluminum (Al), cadmium (Cd), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury, nickel (Ni), and zinc (Zn). Total Kjeldahl nitrogen (TKN) was analyzed using a micro-Kjeldahl method. Total phosphorus (TP) was determined after acid digestion, reduction with molybdenum blue, and colorimetry.

Precipitation was collected whenever a storm event occurred, and the samples were analyzed for all the parameters listed in Table 3, except temperature and suspended solids.

The data were analyzed for differences among years for each site and differences among sites using the combined data from 3 years. Due to the small sample size for each year (i.e., 15 to 28 collections) and the variability of the data, the year-to-year variations were interpreted without a statistical test. Instead, boxplots were used to compare the data graphically (Titus 1987). These plots showed minimum, median and maximum values, as well as the 25th and 75th percentiles (i.e., the lower and upper limits bounding 50% of the data). Comparisons between sites were carried out using a paired t-test procedure (Steel and Torrie 1980). Seasonal export of suspended solids was calculated for sites 1 to 4, which had flow records for 1988 and 1989 (Berry 1991a). The results were compared with the suggested guidelines for freshwater aquatic life, specified by the Canadian Council of Resource and Environment Ministers' Task Force on Water Quality Guidelines (Anon. 1987).

Groundwater

Groundwater was collected using porous ceramic-cup suction lysimeters. The cups had been acid-washed twice in 10% HCl until they showed no contamination of distilled water drawn through them. Lysimeters were placed in two drained and two undrained plots of OG11, and one plot each of drained and undrained OG12 and OG14; OG11 was sampled more intensively because it is the most prevalent peatland type in the study area. In each plot, three lysimeters were installed in a cluster of 1 m diameter on an intermediate-level hummock (between the highest hummock and the lowest hollows). At any one sampling, the water from the three lysimeters was bulked to provide enough water for analysis. Insertion into the peat was accomplished by making an initial hole in the living moss and then pushing the lysimeter down to a depth of 25 cm. This depth sampled the zone just above the assumed maximum rooting depth of black spruce (30 cm), and also sampled water from incoming precipitation percolating downwards through the rooting zone.

Nine collections were made between 29 May and 25 October 1989. The samples were analyzed for the parameters listed in Table 3, with the exception of temperature, suspended solids and alkalinity. These parameters were not tested because of their inapplicability (e.g., suspended solids) or the limited sample quantity (e.g., alkalinity). Collections for Hg analysis were taken in 1989 at the same times as the groundwater samples. Due to the small number of collections, comparisons between drained and undrained plots in each OG were performed using boxplot analysis.

RESULTS AND DISCUSSION

Surface Water Quality

Major Ions

The ion concentrations for each site did not differ greatly among the 3 years. The boxplots were similar in each year and are exemplified by Ca^{2+} concentrations (Fig. 2). Differences among sites were consistent for all ions except SiO_2 (Table 4). The collector ditch (site 4) had higher solute concentrations and greater variability in the data than any other site. This can be attributed to two factors: (1) 87% of the basin was drained (Table 2), and (2) most of the ditches penetrated into the underlying clay. A high proportion of the water leaving the basin

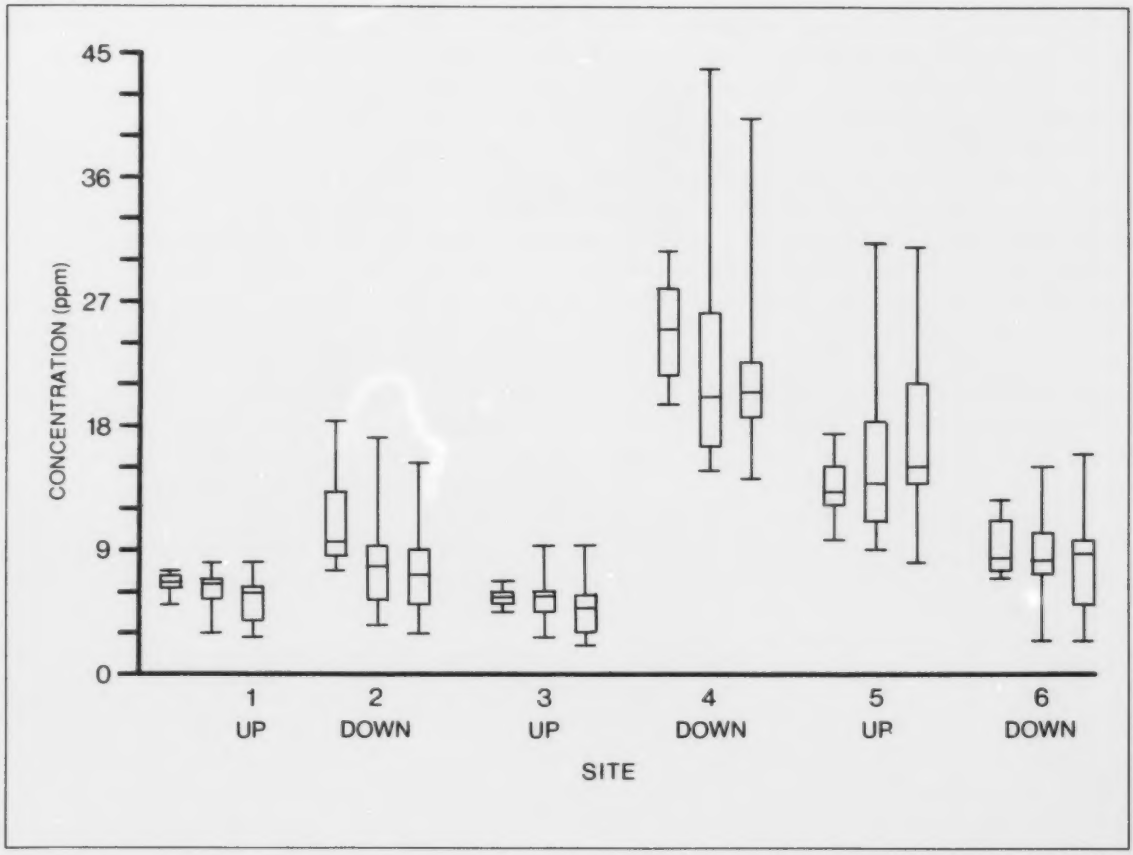

Figure 2. Calcium concentrations in surface water, 1987 to 1989 (Up = upstream of ditch outlets, Dn = downstream of ditch outlets).

was therefore in direct contact with mineral soil. The other downstream treatment sites (sites 2 and 6) had only 9 and 7% of the area of their respective basins drained, with ditches mostly confined to peat, and were influenced to a large degree by subsurface water flow from undrained areas.

The data for the 3 years were combined to test for differences among sites (e.g., Fig. 3 is for combined Ca^{2+} data). The t-test results showed that there were statistically significant differences among the sites. There was some variation between the controls, with four of the seven ions having different concentrations (Table 5). This variation could be a result of the different sizes of streams, areas of basins drained (Table 2), and mixtures of OGs in each basin. The heavily drained basin (site 4) had higher concentrations of all ions than the controls (Table 5). The lightly drained small basin (site 2) was compared with only one control (site 1) because these sites were located in the same water channel upstream and downstream of a series of collector-ditch outlets, and were thus directly comparable. Again, drainage resulted in increased concentrations of all ions. The results were variable for the lightly drained large basin (site 6), in which there were higher Ca^{2+}, Mg^{2+}, K^{+} and Cl^{-} concentrations than in both controls, higher Na^{+} concentrations than in one control, and SO_4^{2-} concentrations that were higher than in one control and lower than in the other. The heavily drained basin (site 4) had greater concentrations of all ions than either of the lightly drained basins (sites 2 and 6). Each lightly drained basin, with approximately the same percentages of drained area, had higher and

Table 4. Boxplot statistics for surface-water ion concentrations (ppm) — combined 1987, 1988 and 1989 data.

		Site					
		1	2	3	4	5	6
Ca^{2+}	Minimum	2.61	2.88	2.23	14.08	8.20	2.40
	25th percentile	5.09	6.40	3.71	18.46	12.35	7.06
	Median	6.24	7.85	5.47	21.05	14.24	8.50
	75th percentile	6.75	9.74	5.96	25.39	16.90	10.09
	Maximum	8.22	18.28	9.41	43.90	31.40	15.91
Mg^{2+}	Minimum	0.59	0.65	0.56	1.67	0.89	0.60
	25th percentile	1.10	1.42	0.84	2.84	2.28	1.50
	Median	1.38	1.76	1.23	3.67	2.67	1.76
	75th percentile	1.51	2.00	1.36	4.31	3.33	2.10
	Maximum	1.89	3.44	4.36	6.60	5.69	3.70
Na^{+}	Minimum	0.46	0.56	0.42	0.95	0.85	0.55
	25th percentile	0.80	0.86	0.64	2.44	1.08	0.86
	Median	0.97	1.16	0.73	2.99	1.18	1.10
	75th percentile	1.05	1.49	0.82	3.50	1.49	1.30
	Maximum	1.54	4.32	9.76	12.75	2.95	2.04
K^{+}	Minimum	0.04	0.08	0.08	0.22	0.09	0.07
	25th percentile	0.13	0.18	0.15	0.33	0.19	0.23
	Median	0.17	0.26	0.20	0.41	0.25	0.32
	75th percentile	0.28	0.40	0.29	0.54	0.31	0.47
	Maximum	1.40	0.82	1.60	1.30	1.30	0.76
Cl^{-}	Minimum	0.22	0.34	0.05	0.86	0.43	0.40
	25th percentile	0.40	0.49	0.24	1.43	0.89	0.60
	Median	0.50	0.59	0.36	1.76	1.01	0.79
	75th percentile	0.69	0.84	0.53	2.02	1.18	0.89
	Maximum	2.45	1.96	3.80	3.09	1.85	1.56
SO_4^{2-}	Minimum	0.52	0.69	0.48	0.99	0.82	0.38
	25th percentile	1.14	1.32	1.23	2.75	1.75	1.13
	Median	1.79	2.00	1.56	3.54	2.22	1.64
	75th percentile	2.42	2.47	1.97	3.89	3.00	2.20
	Maximum	5.60	4.82	5.60	6.07	4.21	3.91
SiO_2	Minimum	0.72	0.73	0.62	1.80	1.22	0.57
	25th percentile	1.57	1.63	1.48	2.53	2.35	1.68
	Median	2.33	2.42	2.49	2.80	3.59	2.28
	75th percentile	3.08	3.20	2.90	3.44	3.83	2.95
	Maximum	4.05	4.24	6.47	4.68	4.46	4.09

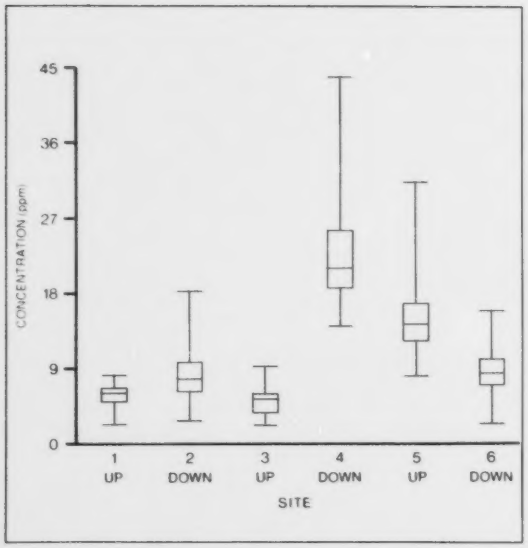

Figure 3. Calcium concentrations in surface water, combined data.

lower concentrations of certain ions than the other basin. This suggests that using the percentage of basin drained is not a good indicator of the potential increase in ion concentration, especially when the percentage is low. Factors other than drainage, such as basin size (Table 2) and the proportions of various OGs in the basin, may be more important.

A direct comparison of sub-treatment site 5 with treatment site 6 showed higher concentrations of most ions at the upstream site (Table 5). This was probably due to the addition of ions from the ditches upstream from site 5. All these ditches were in mineral soil and underwent significant erosion, which enhanced the release of ions. However, because site 6 represented a much larger basin, the ion enhancements as a result of drainage were negated by the time the water reached it.

The concentrations of ions varied over the course of the field season. Concentrations of Ca^{2+}, Mg^{2+}, Na^{+} and SiO_2 were low during snowmelt and high during low-streamflow periods. Conversely, concentrations of K^{+}, Cl^{-} and SO_4^{2-} were high during snowmelt and low during low-streamflow periods. This difference between the two groups of ions was probably a result of different sources of runoff water. The first group of ions are indicators of groundwater that had been in contact with mineral soil (Boelter and Verry 1977). During periods of low streamflow, the groundwater had a greater opportunity to increase its ionic concentration because of its prolonged contact with the underlying mineral soil. During snowmelt, ion concentrations were diluted by the large quantity of runoff, which was prevented from percolating to the groundwater by a layer of frozen peat. Ions in the second group, especially SO_4^{2-}, were abundant in atmospheric deposition (Boelter and Verry 1977, Foster and Nicolson 1988). Median concentrations of K^{+}, Cl^{-} and SO_4^{2-} in the collected precipitation (Table 6) were similar to concentrations in the surface water (Table 4). It is hypothesized that these ions accumulated in the snowpack and were released as a surge during snowmelt. Low concentrations of ions during periods of low streamflow were a result of low ionic inputs from precipitation and runoff.

Despite the increased ion concentrations caused by drainage, no water quality guidelines were exceeded.

Metals

Concentrations of metals were highly variable from year to year, as illustrated by the boxplots for Al (Fig. 4). Control site 3 had higher median concentrations of Fe, Mn and Zn than the other sites, whereas treatment site 6 had the highest concentration of Al and the second highest concentrations of Fe, Cu, Mn and Zn (Table 7). The concentrations of Cd, Ni and Pb were at or below the detection limit in >80% of the collections. Similarly, Hg concentrations were below the detection limit in both collections.

The effect of drainage on metal concentrations varied. All three treatment sites had significantly higher concentrations of Al, Cu and Mn than one or both controls (Table 5). The two lightly drained basins had higher Fe concentrations than

Table 5. Summary of t-test results for surface water[a].

Major ions	Sites	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	SiO_2
Controls	1 vs. 3	>	=	=	<	>	>	=
Controls versus heavily drained	1 vs. 4	<	<	<	<	<	<	<
	3 vs. 4	<	<	<	<	<	<	<
Control versus lightly drained (small basin)	1 vs. 2	<	<	<	<	<	<	<
Controls versus lightly drained (large basin)	1 vs. 6	<	<	<	<	<	>	=
	3 vs. 6	<	<	=	<	<	<	=
Heavily drained versus lightly drained (small basin)	4 vs. 2	>	>	>	>	>	>	>
Heavily drained versus lightly drained (large basin)	4 vs. 6	>	>	>	>	>	>	>
Lightly drained (small) versus lightly drained (large)	2 vs. 6	<	<	>	<	>	>	=
Drained up verses drained down	5 vs. 6	>	>	>	<	>	>	>

Metals	Sites	Al	Fe	Cu	Pb	Mn	Zn	Cd	Ni	Hg
Controls	1 vs. 3	=	<	=	=	<	<	=	=	=
Controls versus heavily drained	1 vs. 4	<	=	<	=	<	=	=	=	=
	3 vs. 4	<	=	<	=	>	>	=	=	=
Control versus lightly drained (small basin)	1 vs. 2	<	<	<	=	<	=	=	=	=
Controls versus lightly drained (large basin)	1 vs. 6	<	<	<	=	<	<	=	=	=
	3 vs. 6	<	=	=	=	>	=	=	=	=
Heavily drained versus lightly drained (small basin)	4 vs. 2	>	=	=	=	>	=	=	=	=
Heavily drained versus lightly drained (large basin)	4 vs. 6	=	=	=	=	=	<	=	=	=
Lightly drained (small) versus lightly drained (large)	2 vs. 6	<	<	=	=	<	=	=	=	=
Drained up versus drained down	5 vs. 6	>	<	=	=	<	<	=	=	=

Nitrogen and Phosphorus	Sites	NH_4^{+}–N	$(NO_2^{-} + NO_3^{-})$–N	TP	TKN
Controls	1 vs. 3	=	=	=	=
Controls versus heavily drained	1 vs. 4	<	=	<	=
	3 vs. 4	<	=	=	=
Control versus lightly drained (small basin)	1 vs. 2	=	=	=	=
Controls versus lightly drained (large basin)	1 vs. 6	=	=	=	=
	3 vs. 6	=	=	=	=
Heavily drained versus lightly drained (small basin)	4 vs. 2	>	=	>	=
Heavily drained versus lightly drained (large basin)	4 vs. 6	>	=	>	=
Lightly drained (small) versus lightly drained (large)	2 vs. 6	=	=	=	=
Drained up versus drained down	5 vs. 6	=	=	=	<

(cont'd)

Table 5. Summary of t-test results for surface water (concl.)[a].

Other analyses	Sites	pH	Alkal-inity	Temp.	Conductivity	Suspended solids
Controls	1 vs. 3	>	=	=	>	<
Controls versus heavily drained	1 vs. 4	<	<	<	<	<
	3 vs. 4	<	<	<	<	<
Control versus lightly drained (small basin)	1 vs. 2	<	<	<	<	<
Controls versus lightly drained (large basin)	1 vs. 6	<	<	<	<	<
	3 vs. 6	<	<	<	<	<
Heavily drained versus lightly drained (small basin)	4 vs. 2	>	>	>	>	>
Heavily drained versus lightly drained (large basin)	4 vs. 6	>	>	=	>	>
Lightly drained (small) versus lightly drained (large)	2 vs. 6	>	<	<	<	=
Drained up versus drained down	5 vs. 6	>	>	<	>	=

[a]For comparisons of A versus B, the following codes are used: > A significantly greater than B
< A significantly less than B
= no significant difference at the 95% level

Table 6. Descriptive statistics of precipitation — combined 1987, 1988 and 1989 data.

	Minimum	25th percentile	Median	75th percentile	Maximum
Ca^{2+} (ppm)	0.31	0.43	0.52	0.71	1.00
Mg^{2+}	0.04	0.07	0.08	0.11	0.17
Na^{+}	0.12	0.16	0.17	0.24	0.34
K^{+}	0.08	0.17	0.23	0.32	0.54
Cl^{-}	0.13	0.20	0.27	0.34	0.44
SO_4^{2-}	0.94	1.88	2.29	2.92	3.77
SiO_2	0.00	0.01	0.02	0.03	0.07
NH_4^{+}–N (ppb)	1.0	38.0	103.0	214.5	431.0
$(NO_2^{-} + NO_3^{-})$–N	75.0	82.5	136.0	423.5	675.0
TP	8.6	15.6	29.2	42.3	48.7
TKN (ppm)	0.00	0.17	0.41	0.94	0.97
Al (ppb)	10	17	19	25	34
Fe	4	8	13	16	18
Cu	1	2	2	4	8
Pb	1	2	5	6	17
Mn	3	5	8	14	22
Zn	99	126	150	253	464
Cd	<0.2	<0.2	<0.2	<0.2	<0.2
Ni	<2.0	<2.0	<2.0	<2.0	<2.0
pH	2.9	3.6	3.8	4.0	4.2
Alkalinity (mg/L $CaCO_3$)	0	0	0	0	0
Conductivity (µS/cm)	9	16	18	25	30

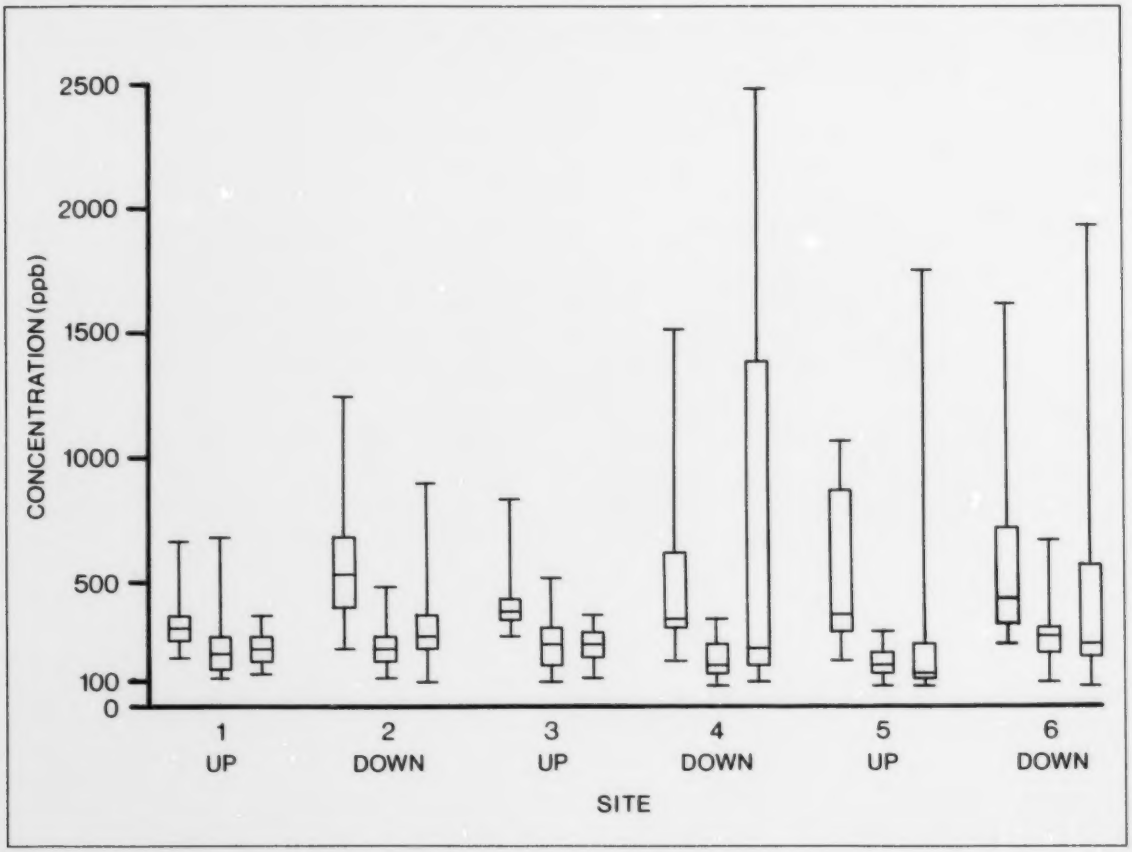

Figure 4. Aluminum concentrations in surface water, 1987 to 1989.

control site 1, but the heavily drained basin did not. As a result of the variability of the data, the comparison of control site 1 with treatment site 2 is, perhaps, more informative because of their relationship, described previously. In this case, drainage resulted in higher concentrations of Al, Fe, Cu and Mn. There were no significant differences in concentrations of the other metals. The major differences among the three treatments appeared to be between the two lightly drained basins. The large basin had higher concentrations of Al, Fe and Mn than the small basin, suggesting again the influence of the different OG composition within their respective basins.

Except for Cd, Ni, Pb and Hg, concentrations of metals at all sites were low during low-streamflow periods and high during storm events. This suggests that either as the water table rose or as precipitation percolated into the water table, metals were drawn from the upper peat layers. In some peat profiles, concentrations of Fe, Al, Mn and Cu in groundwater have been noted to decrease as depth increases (Pakarinen et al. 1980, Lapakko 1985). Hence, it is possible that the increases in the levels of some metals in streams could be caused by rainwater flushing the minerals from the upper horizons of peat.

The above explanation may not apply to all metals. For example, Zn concentrations were particularly high in the precipitation (Table 6) compared with the surface water concentration, and may have been a source of increased surface water concentration during storm events.

Water quality guidelines (Table 8) were exceeded only a few times during the 3 years by

Table 7. Descriptive statistics for surface-water trace metal concentrations (ppb) — combined 1987, 1988 and 1989 data.

		Site					
		1	2	3	4	5	6
Al	Minimum	110	93	108	82	76	81
	25th percentile	195	225	195	160	133	220
	Median	243	276	268	247	190	294
	75th percentile	311	411	344	373	300	390
	Maximum	680	1245	834	2484	1754	1929
Fe	Minimum	140	130	140	150	130	140
	25th percentile	269	300	310	215	187	363
	Median	350	364	489	270	231	450
	75th percentile	411	496	620	443	324	560
	Maximum	660	1178	1154	1789	1154	1112
Cu	Minimum	2.0	2.0	1.1	1.6	1.0	1.0
	25th percentile	2.5	2.6	2.5	2.5	2.3	2.6
	Median	3.4	4.0	3.7	4.3	3.0	4.2
	75th percentile	4.9	7.7	6.1	8.6	5.6	6.6
	Maximum	13.1	21.3	11.1	18.9	14.7	15.5
Hg		<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Pb	Minimum	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
	25th percentile	2.0	2.0	2.0	2.0	2.0	2.0
	Median	2.0	2.0	2.0	2.0	2.0	2.0
	75th percentile	2.0	2.0	2.0	2.1	2.0	2.0
	Maximum	8.4	13.0	15.5	14.9	4.1	12.1
Mn	Minimum	<2.0	3.1	2.5	2.0	2.0	<2.0
	25th percentile	11.4	11.8	23.8	13.3	4.8	17.6
	Median	14.3	15.7	33.7	20.6	8.8	23.9
	75th percentile	22.5	22.2	42.7	33.3	13.0	33.5
	Maximum	68.1	85.8	149.0	67.0	32.3	112.0
Zn	Minimum	5.0	3.0	5.0	3.0	5.0	5.0
	25th percentile	7.6	8.0	9.1	5.7	5.2	8.2
	Median	9.0	10.0	10.9	8.6	8.0	10.2
	75th percentile	12.5	14.0	14.3	13.2	10.7	14.5
	Maximum	30.0	34.0	22.7	23.4	19.3	30.0
Cd	Median	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2
Ni	Median	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0

Table 8. Water quality guidelines for freshwater aquatic life (Anon. 1987).

Al	5 ppb, pH < 6.5 100 ppb, pH > 6.5	Ni	25 ppb
Fe	300 ppb	Zn	30 ppb
Pb	1 – 2 ppb	pH	6.5 – 9.0
Cd	0.2 ppb	Suspended solids	increase 10 mg/L, < 100mg/L increase 10%, >100 mg/L
Cu	2.0 ppb	NH_4^+–N	470 – 2200 ppb
Hg	0.1 ppb		

all the metals except Al, Fe and Cu. These three metals had consistently higher concentrations at all sites than the water quality guidelines recommended. Concentrations of Al (Fig. 5) and Fe were particularly high. Even the minimum Al concentrations were near or above the limits. The similarity between the controls (sites 1 and 3) and the treatments (sites 2 and 6) indicates that there were high naturally occurring concentrations (Table 7). These values were within the range reported by Hillman (1988) for streams influenced by drainage ditches in Alberta. Because the detection limit of the Hg analysis was 1.0 ppb, the concentrations could not be compared with the guideline of 0.1 ppb.

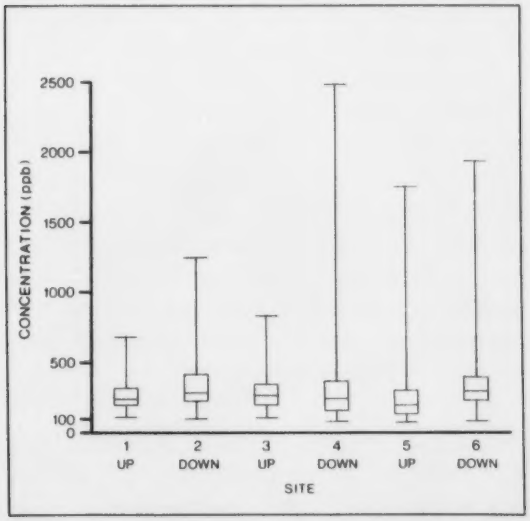

Figure 5. Aluminum concentrations in surface water, combined data.

However, it can be stated that there were no high concentrations of Hg.

Nitrogen and Phosphorus

As with the metals, these parameters varied among years and sites (Table 9). The paired t-tests showed that the only effect drainage had was to increase the concentrations of NH_4^+–N and total P in the heavily drained area (Table 5). These increases were possibly a result of increased decomposition of the upper peat layers in response to increased aeration (Knighton and Stiegler 1980, Lundin 1988). The lightly drained basins did not exhibit any increases because the inputs from the drained areas were small in relation to those from undrained areas within their basins.

Increased concentrations of (NO_2^- + NO_3^-)–N were not observed, possibly because of the acidic conditions within the peat of both drained and undrained areas (see the section below on groundwater pH), which may have inhibited nitrification (Salisbury and Ross 1978, Hynninen and Sepponen 1983). Heavily drained site 4 had the greatest maximum concentration of (NO_2^- + NO_3^-)–N, which may have been caused by the ditches intercepting precipitation that had high concentrations of nitrogen (Table 6).

No water quality guidelines, where stated, were exceeded.

Table 9. Descriptive statistics of surface-water nitrogen compounds and total P concentrations (ppb) — combined 1987, 1988 and 1989 data.

		Site					
		1	2	3	4	5	6
NH_4^+–N	Minimum	5.0	6.1	6.8	5.1	5.4	6.8
	25th percentile	12.5	11.9	12.6	10.4	8.6	12.0
	Median	18.3	17.7	21.5	21.2	18.1	17.3
	75th percentile	30.3	28.7	30.6	42.1	28.2	24.5
	Maximum	87.5	75.7	70.5	152.8	102.6	98.7
$(NO_2^- + NO_3^-)$–N	Minimum	1.0	1.0	1.0	1.0	1.0	1.0
	25th percentile	8.0	6.5	9.0	6.0	17.5	6.5
	Median	20.0	20.0	28.0	17.0	34.0	15.0
	75th percentile	38.0	43.0	53.5	53.0	59.0	24.0
	Maximum	241.0	438.0	712.0	934.0	568.0	121.0
TP	Minimum	6.8	5.1	10.4	12.7	7.0	9.5
	25th percentile	14.3	15.4	16.9	18.6	11.6	16.1
	Median	18.9	19.5	20.4	23.3	14.8	22.9
	75th percentile	27.2	24.7	25.6	59.2	27.3	32.5
	Maximum	75.7	142.0	430.5	179.0	223.0	209.0
TKN	Minimum	420	400	370	210	10	460
	25th percentile	580	550	600	640	570	610
	Median	680	640	770	740	680	750
	75th percentile	860	800	870	860	850	940
	Maximum	2640	2780	1290	1970	1150	1440

pH, Alkalinity, Temperature and Conductivity

There were significant differences in pH values among years. Values at all sites were up to three-quarters of a unit higher in 1987 than in the other 2 years (Fig. 6). The pH values in 1988 and 1989 were quite similar. Drainage increased pH significantly (Fig. 7, Tables 10 and 5). The heavily drained basin had higher pH values than either lightly drained basin, primarily as a result of water contact with mineral soil and less-acidic deep peat layers. The lightly drained small basin had higher pH values than the lightly drained large basin, probably because there was less water from the undrained portion of the small basin to dilute the effect of the pH rise (Heikurainen et al. 1978, Hynninen and Sepponen 1983).

The minimum pH values occurred during the snowmelt period of 1989. The pH of the snow just before snowmelt was 3.2, which resulted in a surge of fairly acidic streamflow. In general, pH values were low during high-streamflow periods and high during low-streamflow periods. This situation was caused by the low pH of the precipitation, which had values ranging from 2.9 to 4.2 (Table 6). These low pH values were possibly a result of the long-range transport of atmospheric pollutants from industrial areas southwest of the study area.

Drainage significantly increased alkalinity (Table 5). However, all sites, except heavily drained site 4 and site 5, had median alkalinity (as $CaCO_3$) values less than 24 mg/L, indicating a poor buffering capacity (Anon. 1981a). The

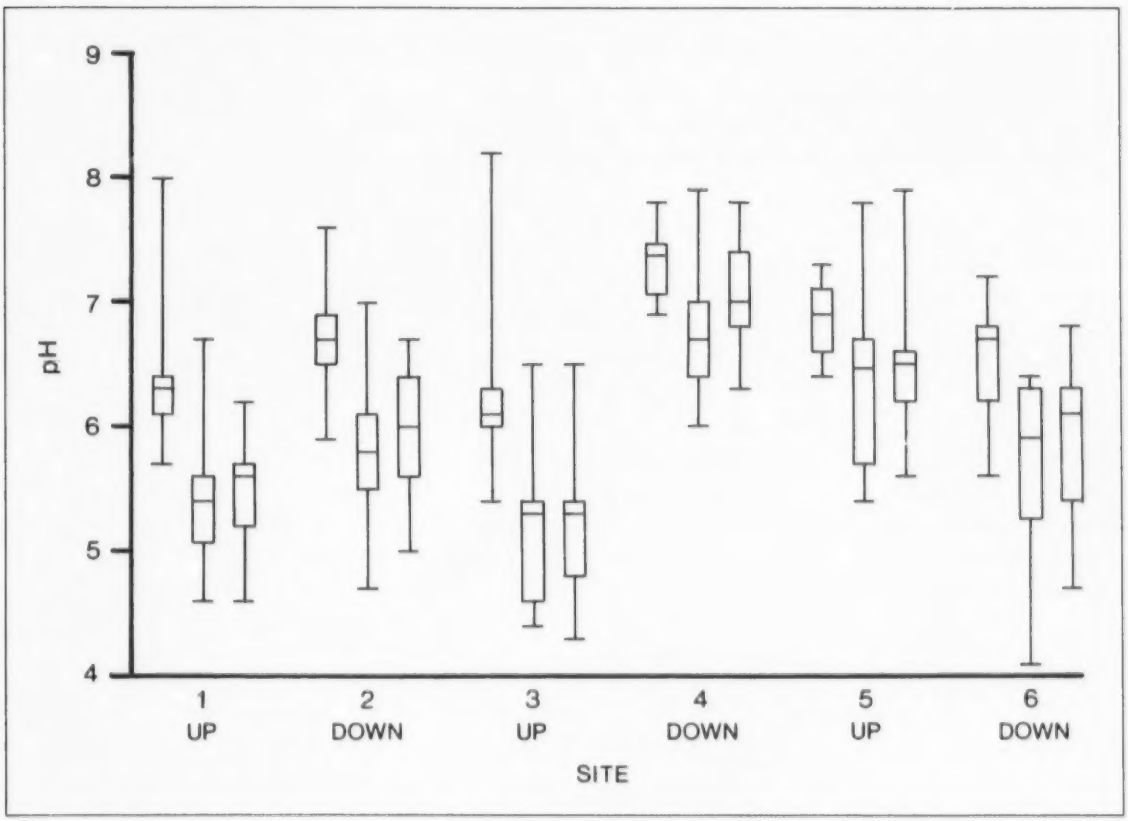

Figure 6. pH in surface water, 1987 to 1989.

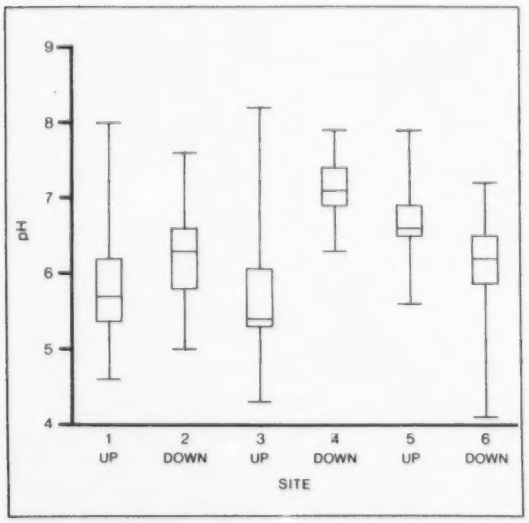

Figure 7. pH in surface water, combined data.

large increases at sites 4 and 5 were due to the influence of the mineral soil exposure within the ditches.

Water temperatures varied according to time of season, with low temperatures in early spring and late autumn, and high temperatures in mid-to-late summer (Table 11). The paired t-test results showed that drainage significantly increased temperatures, probably by increasing ground temperatures and increasing the exposure of water in the ditches to solar radiation (Table 5). In absolute terms, though, the 25th and 75th percentile and median values were increased by only 1 to 2°C.

The variability in conductivity (Table 11) and its increase in response to drainage (Table 5) were directly related to the increase in the ionic concentrations previously discussed.

Table 10. Boxplot statistics for surface-water pH and alkalinity — combined 1987, 1988 and 1989 data.

		Site					
		1	2	3	4	5	6
pH	Minimum	4.6	5.0	4.3	6.3	5.6	4.1
	25th percentile	5.4	5.8	5.3	6.9	6.5	5.9
	Median	5.7	6.3	5.4	7.1	6.6	6.2
	75th percentile	6.2	6.6	6.1	7.4	6.9	6.5
	Maximum	8.0	7.6	8.2	7.9	7.9	7.2
Alkalinity	Minimum	0	2	0	9	15	0
(mg/L $CaCO_3$)	25th percentile	2	6	3	37	25	8
	Median	5	10	4	47	31	14
	75th percentile	8	18	9	70	44	24
	Maximum	37	44	128	115	89	80

Table 11. Descriptive statistics for surface-water physical parameters — combined 1987, 1988 and 1989 data.

		Site					
		1	2	3	4	5	6
Temperature	Minimum	1	1	1	1	1	1
(°C)	25th percentile	5	6	7	7	8	7
	Median	11	11	11	12	13	12
	75th percentile	13	14	14	15	16	17
	Maximum	22	24	22	30	23	25
Conductivity	Minimum	15	19	15	70	55	19
(µS/cm)	25th percentile	30	40	25	95	70	40
	Median	40	45	30	110	85	48
	75th percentile	40	55	35	150	105	60
	Maximum	50	95	75	280	185	95
Suspended solids	Minimum	0	0	0	0	0	0
(mg/L)	25th percentile	0	4	1	6	5	3
	Median	4	7	5	12	8	8
	75th percentile	9	15	12	87	15	15
	Maximum	25	215	31	540	137	77

No water quality guidelines, where stated, were exceeded. In fact, drainage improved the pH and alkalinity conditions for aquatic life.

Suspended Solids

Concentrations of suspended solids at the treatment sites were quite variable from year to year (Fig. 8), and were dependent on storm events. The suspended solids from the sites were almost exclusively mineral sediment. The water quality guidelines were exceeded by the treatment sites during smaller storm streamflows and by all sites during major storm streamflows. Drainage increased not only the concentrations of suspended solids (Fig. 9, Tables 11 and 5), but also the seasonal export of solids (Table 12). The export in 1989 was much less than in 1988 because of the lower streamflows in 1989. It should be noted that treatment site 4 was located upstream of any sedimentation ponds. The high concentrations and exports may not have been indicative of what actually entered the creek.

Although treatment site 2 was downstream of sedimentation ponds, it still showed increased concentrations and exports of suspended solids. Examination of the pond data (Fig. 10, Table 13) showed that neither pond was completely effective in removing sediment. The concentrations of sediment in the ditches was higher downstream of the ponds than upstream, showing that sediment was transported out of the ponds. Both ponds were nearly filled to capacity with sediment and, if cleaned, would likely have become more effective (Heikurainen and Joensuu 1981).

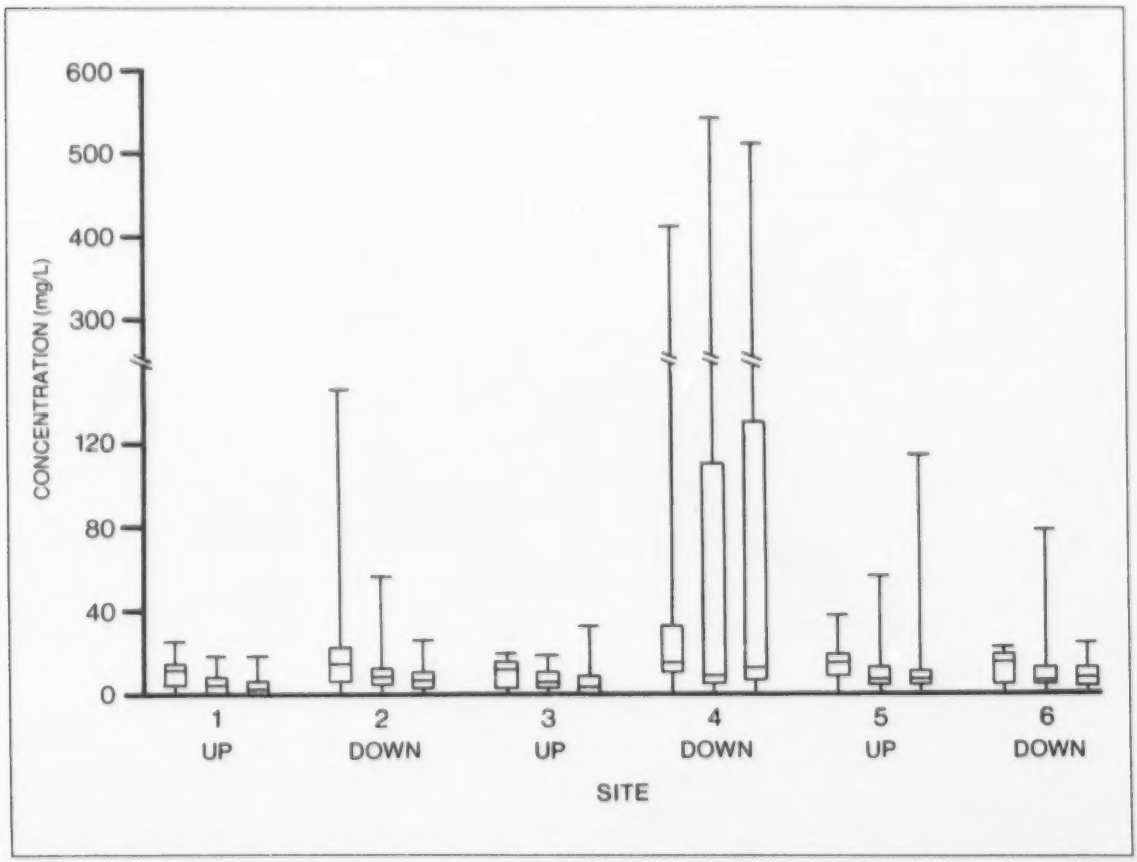

Figure 8. Suspended solids concentrations in surface water, 1987 to 1989.

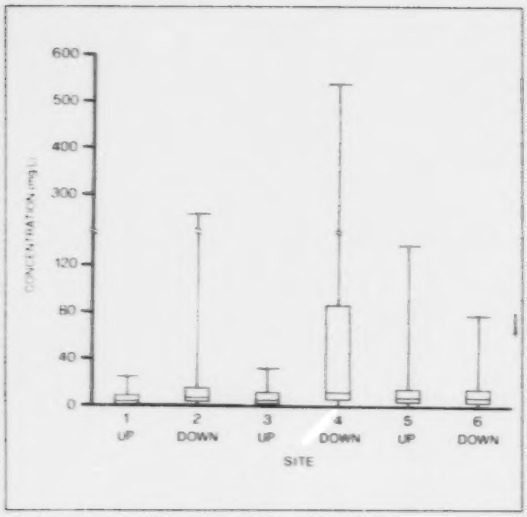

Figure 9. Suspended solids concentrations in surface water, combined data.

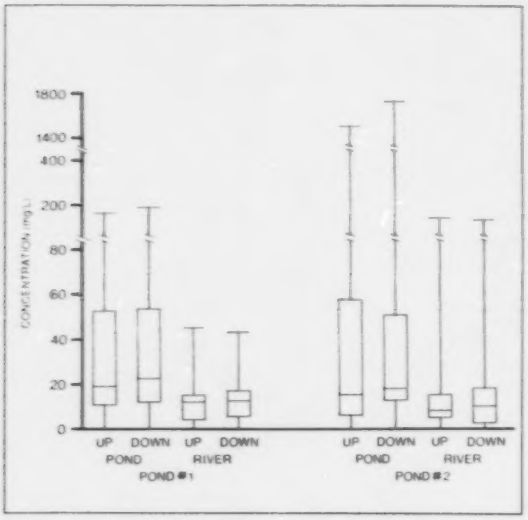

Figure 10. Suspended solids concentrations in surface water at sedimentation ponds, combined data.

Table 12. Export of suspended solids (kg/ha/season).

	Site			
Year	1	2	3	4
1988	36	62	46	733
1989	14	38	15	383

Groundwater quality

Results for groundwater analyses are presented in Tables 14 to 18 and Figures 11 to 17. The samples for OG11 were the most reliable because there were two plots representing both drained and undrained sites, and because the vegetation and site conditions were fairly similar for all plots. The samples for OG12 and OG14 were less reliable because each OG had only one plot each for drained and undrained sites, and the plots of each paired comparison contained different vegetation types. Furthermore, the undrained controls for OG12 and OG14 were on wetter and deeper peats, and were located further from uplands, than the drained plots were before drainage. These conditions suggest different nutrient regimes for these pairs of drained and undrained plots.

Major ions

Drainage of OG11 resulted in increased concentrations of all ions, except K^+, which decreased (Tables 14, 15). The increase in the median concentrations ranged from 3% for Na^+ to 95% for Ca^{2+} (Fig. 11). The increases in ions could be explained by increased decomposition of the drained peat layer as a result of increased aeration and subsequent vertical transport of the ions to the level of the lysimeter sampling. The decrease in K^+ may be explained in two ways, either by rapid uptake by the vegetation, which is able to grow better with more aeration in the rooting horizons, or by a rapid leaching of K^+ below the level of the lysimeters (more leaching than the other ions, which showed increases in their concentrations).

The results for OG12 and OG14 differed from those of OG11, as well as from each other (Tables 14 and 15). OG12 showed an increase in K^+ and decreases in Cl^- and SiO_2 in drained plots; OG14 showed decreases in Mg^{2+}, Na^+ and SiO_2, and no change for Cl^-, in drained plots. The noncomparability of the paired sites for OG12 and OG14 may explain some of these differences. It is interesting to note, however,

Table 13. Boxplot statistics for surface-water concentrations of suspended solids (mg/L) at sedimentation ponds — combined 1987 and 1988 data.

	Sedimentation pond							
	1				2			
	Up Pond[a]	Down Pond[b]	Up River[c]	Down River[d]	Up Pond[a]	Down Pond[b]	Up River[c]	Down River[d]
Minimum	0	0	0	0	0	0	0	0
25th percentile	11	12	4	6	6	13	5	3
Median	19	23	12	13	15	18	8	10
75th percentile	53	54	15	17	58	51	15	18
Maximum	168	190	45	43	1502	1719	137	131

[a] Up pond = ditch leading into pond
[b] Down pond = ditch leading out of pond
[c] Up river = river upstream of pond outlet
[d] Down river = river downstream of pond outlet

that Ca^{2+} and SO_4^{2-} were consistently greater in the drained plots in all three OGs. The SO_4^{2-} ion does not bind effectively to organic matter and so was readily available in the soil solution (Salisbury and Ross 1978).

Metals

Concentrations of Al, Fe and Mn increased as a result of drainage in OG11 (Fig. 13 and 14, Tables 15 and 16). On the other hand, these elements and Zn decreased with drainage in OG12 and OG14. Cu showed an increase with drainage in OG14.

It is difficult to make any meaningful interpretations of these changes. The metals may show different patterns with depth in the different OGs. For example, some studies have reported decreases in Al and Fe with depth (e.g., Pakarinen et al. 1980, Lappako 1985), whereas others have reported increases with depth (e.g., Pakarinen and Gorham 1983). When ion concentrations are higher in the upper strata, increased decomposition after drainage may release bound forms, which would explain increases of the ion levels in the groundwater. One must also take into account the ion states under oxidized (aerobic) and reduced (anaerobic) conditions. With drainage, the reduced forms of some ions will become oxidized; the oxidized forms are often less mobile and less subject to leaching than reduced forms. One must also consider the location of the lysimeter in relation to the groundwater table.

It was previously shown (in the section on Surface-water Metals) that concentrations of Al and Fe in surface water increased after drainage. It is tempting to relate these increases to increases observed for the same ions in the sampled groundwaters of drained OG11, and subsequent flushing of the ions into the drainage ditches and streams. The fact that OG11 is the most important vegetation type in the Wally Creek area complements such a hypothesis. However, the additional Al and Fe could also be derived from the recently exposed mineral soils at the bottoms of many drainage ditches.

Nitrogen Compounds and Phosphorus

Drainage in OG11 increased (NO_2^- + NO_3^-)–N, total P and TKN, but did not change NH_4^+–N (Fig. 15, Tables 15 and 17). These changes were probably owing to increased decomposition

Table 14. Descriptive statistics for groundwater ion concentrations (ppm) – combined 1987, 1988 and 1989 data.

		Operational group (OG)					
		11	11C	12	12C	14	14C
Ca^{2+}	Minimum	3.93	2.78	4.48	1.45	1.65	2.80
	25th percentile	6.91	3.24	6.10	1.96	2.99	3.28
	Median	8.29	4.26	6.57	3.78	4.06	3.99
	75th percentile	10.13	5.96	7.10	4.56	4.83	4.72
	Maximum	10.60	6.75	7.64	5.69	5.61	5.16
Mg^{2+}	Minimum	0.88	0.84	1.88	0.34	0.23	0.60
	25th percentile	1.64	0.94	2.08	0.45	0.35	0.64
	Median	1.86	1.22	2.68	0.88	0.49	0.91
	75th percentile	2.05	1.34	2.85	1.04	0.55	1.00
	Maximum	2.42	1.86	2.93	1.23	0.65	1.02
Na^{+}	Minimum	0.43	0.70	1.11	0.43	0.36	0.69
	25th percentile	0.69	0.75	1.17	0.76	0.81	0.91
	Median	0.82	0.80	2.24	1.20	0.88	1.00
	75th percentile	0.97	0.87	2.41	1.27	0.95	1.10
	Maximum	1.13	1.47	2.65	1.33	1.05	1.32
K^{+}	Minimum	0.23	0.47	0.39	0.18	0.10	0.06
	25th percentile	0.35	0.57	0.47	0.21	0.13	0.09
	Median	0.45	0.77	0.63	0.29	0.17	0.20
	75th percentile	0.66	0.86	0.84	0.45	0.20	0.23
	Maximum	1.06	1.14	1.01	0.70	0.42	0.33
Cl^{-}	Minimum	0.22	0.27	1.11	0.15	0.30	0.34
	25th percentile	0.56	0.43	1.36	0.44	0.41	0.41
	Median	0.74	0.55	1.56	0.52	0.50	0.52
	75th percentile	0.94	0.59	1.64	0.98	0.68	0.67
	Maximum	1.95	1.25	2.19	1.23	0.93	1.16
SO_4^{2-}	Minimum	2.41	3.16	6.30	0.18	1.56	0.11
	25th percentile	5.35	4.08	7.00	0.23	2.53	0.14
	Median	7.43	4.55	7.81	0.44	4.89	0.18
	75th percentile	8.94	5.65	8.76	0.71	6.07	0.37
	Maximum	11.30	6.54	8.92	1.26	6.52	0.49
SiO_2	Minimum	2.26	2.64	2.70	2.55	1.13	4.36
	25th percentile	4.96	2.95	3.08	3.61	1.40	5.17
	Median	5.76	4.13	3.23	6.13	1.56	5.59
	75th percentile	5.97	6.28	4.08	6.54	1.64	5.74
	Maximum	7.14	6.89	5.23	7.38	1.86	6.25

Table 15. Summary of boxplot results for groundwater quality, undrained vs. drained, on the basis of median and quartile data[a].

	Operational group (OG)		
Major ions	11	12	14
Ca^{2+}	<	<	<
Mg^{2+}	<	<	>
Na^{+}	<	<	>
K^{+}	>	<	>
Cl^{-}	<	>	=
SO_4^{2-}	<	<	<
SiO_2	<	>	>
Metals			
Al	<	>	>
Fe	<	>	>
Cu	=	=	<
Hg	=	=	=
Pb	=	=	=
Mn	<	=	>
Zn	=	=	>
Nitrogen and Phosphorus			
NH_4^{+}–N	=	>	<
$(NO_2^{-} + NO_3^{-})$–N	<	=	<
TP	<	>	>
TKN	<	>	>
Other analyses			
pH	<	<	>
Conductivity	<	<	<

[a]For the comparison of drained vs. undrained, the following codes were used:
< undrained less than drained
> undrained greater than drained
= undrained similar to drained

by microorganisms. The lack of change in NH_4^{+}–N could be explained by increased plant uptake or increased nitrification.

Drainage in OG14 yielded increased $(NO_2^{-} + NO_3^{-})$–N and NH_4^{+}–N (Fig. 15, Tables 15 and 17). The increased NH_4^{+}–N could be explained by less plant uptake in this poorly forested site type compared within OG11, and/or by lack of nitrification.

The decrease of NH_4^{+}–N in the drained OG12 could be explained by rapid plant uptake of this ionic form as it became available during decomposition; OG12 is well forested, as is OG11.

Drainage in OG12 and OG14 decreased the TKN and total P (Fig. 16, Tables 15 and 17). It is difficult to explain these changes, since one

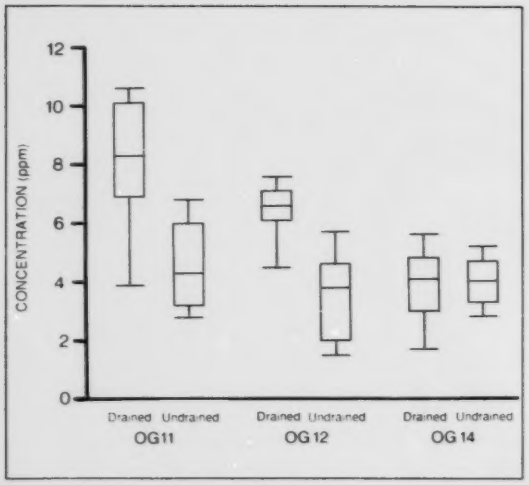

Figure 11. Calcium concentrations in ground water, 1989.

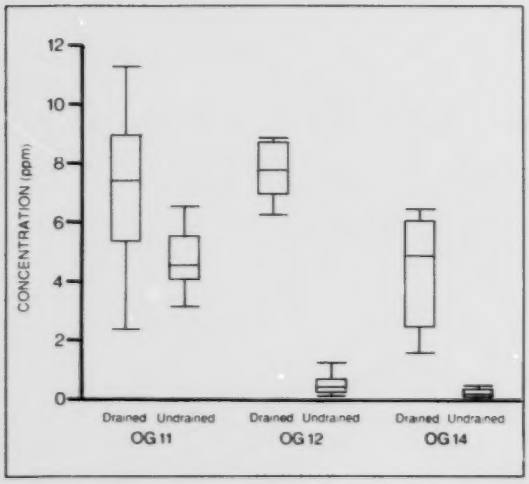

Figure 12. Sulphate concentrations in ground water, 1989.

would expect increased decomposition and higher totals, as was obtained in OG11.

pH and Conductivity

The pH values for OG11 and OG12 were higher in the drained plots than the undrained, whereas the pH values for OG14 were significantly lower in the drained plots (Fig. 17, Table 18). As previously noted, more confidence should be given to the results for OG11. It is possible that rises in pH could be explained by the influence of released cations.

Some literature suggests that pH generally decreases in peat when it is dried and then re-wetted before measuring (e.g., Holmen 1964). However, the peat at the 25 cm depth and layers immediately above may have never been completely dried or may have dried only at the surface. Hence, the observation of rising pH may be more typical for drained peatlands, but this must be confirmed by sampling groundwaters before and after drainage.

These differences should be interpreted with caution. It is known that pH varies greatly among hummocks within the same site, among sites with different dominant mosses, and with depth of peat. The placement of the lysimeter cups was always at 25 cm, and the cups were undoubtedly in different peat layers, varying from surficial fibric to more decomposed mesic peat. Hence, differences in pH and chemistry could be related to a higher initial Ca^{2+} content in the layers sampled in the drained plots. It is known from the literature that a direct relationship exists between pH and Ca^{2+} in the peat (Holmen 1964).

There was a higher mean conductivity in the drained plots than in the undrained plots for all three OGs (Tables 15 and 17). These differences could have been related to releases of ions in the drained plots. However, the differences also could relate to initially higher ion concentrations in the drained plots compared with the undrained.

CONCLUSIONS

Drainage affected the quality of surface water and groundwater by increasing or decreasing the concentrations and values of the various parameters. Water quality guidelines for surface water were exceeded by Al, Fe and Cu at both drained and undrained sites, indicating naturally occurring high concentrations of these metals.

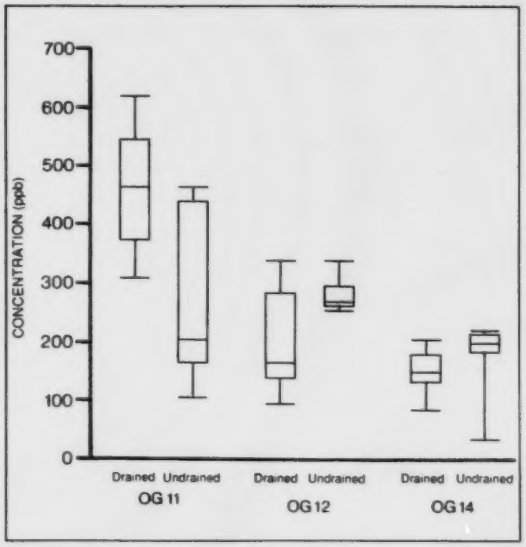

Figure 13. Aluminum concentrations in ground water, 1989.

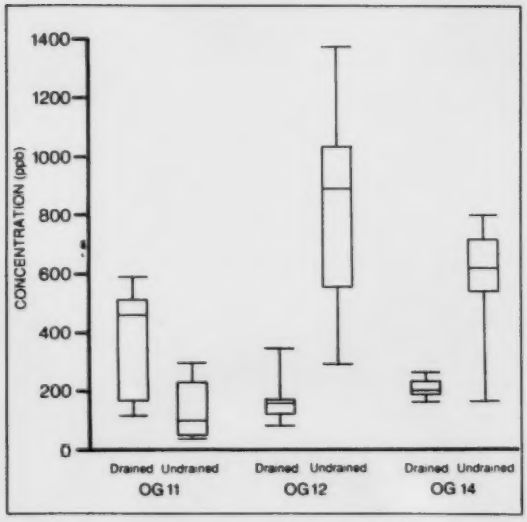

Figure 14. Iron concentrations in ground water, 1989.

Concentrations of suspended solids that exceeded guidelines during storm events were the result of sedimentation ponds that required cleaning. Overall, the results of this study show that drainage has not significantly degraded downstream or on-site water quality. Indeed, pH and alkalinity conditions were improved for aquatic life.

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Table 16. Boxplot statistics for groundwater trace metal concentrations (ppb) — combined 1987, 1988 and 1989 data.

		Operational group (OG)					
		11	11C	12	12C	14	14C
Al	Minimum	310	107	93	254	87	35
	25th percentile	374	167	140	264	133	185
	Median	463	204	167	272	150	200
	75th percentile	546	442	285	297	179	216
	Maximum	619	464	342	340	207	218
Fe	Minimum	117	40	80	293	157	156
	25th percentile	169	49	122	552	188	532
	Median	460	99	157	884	199	612
	75th percentile	513	232	168	1028	226	708
	Maximum	591	296	343	1368	260	793
Cu	Minimum	11.0	12.1	12.1	4.8	8.2	4.0
	25th percentile	15.4	14.2	15.2	10.8	16.8	8.2
	Median	15.6	15.9	16.2	13.1	19.2	14.2
	75th percentile	17.0	18.9	18.2	16.6	24.1	17.8
	Maximum	32.3	21.2	19.8	19.2	31.6	18.8
Hg		<1.0	<1.0	<1.0	<1.0	<1.0	<1.0
Pb	Minimum	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
	25th percentile	<2.0	<2.0	<2.0	<2.0	<2.0	<2.0
	Median	<2.0	<2.0	<2.0	<2.0	2.3	<2.0
	75th percentile	2.0	<2.0	<2.0	<2.0	3.3	<2.0
	Maximum	4.4	3.2	<2.0	2.8	3.6	4.9
Mn	Minimum	20.7	17.9	23.1	16.9	2.7	14.8
	25th percentile	33.6	18.8	28.7	20.5	3.4	21.3
	Median	74.6	21.5	37.8	32.0	4.8	23.4
	75th percentile	122.0	46.7	41.0	33.1	10.0	24.5
	Maximum	161.0	68.3	45.0	34.4	19.0	27.4
Zn	Minimum	24.0	21.0	18.0	24.0	21.0	22.0
	25th percentile	31.0	29.0	22.5	27.0	27.4	48.0
	Median	39.0	35.0	27.5	32.5	32.0	61.5
	75th percentile	55.0	42.0	30.5	62.5	44.5	66.0
	Maximum	62.0	54.0	47.9	90.0	57.0	90.0

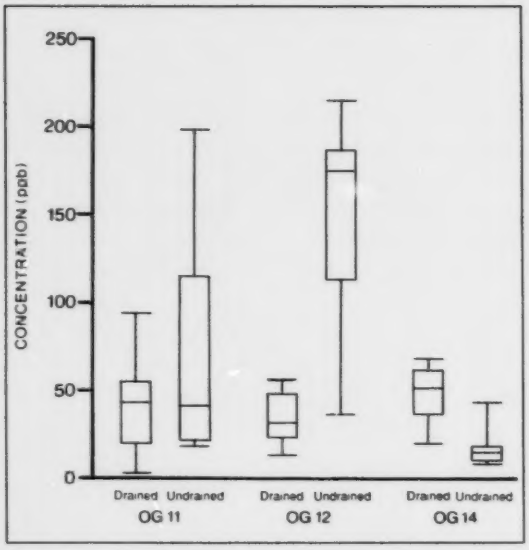

Figure 15. Ammonium-nitrogen concentrations in ground water, 1989.

Table 17. Boxplot statistics for groundwater nutrient concentrations (ppb) — combined 1987, 1988 and 1989 data.

		Operational group (OG)					
		11	11C	12	12C	14	14C
NH_4^+–N	Minimum	2	18	13	36	20	9
	25th percentile	22	21	24	114	37	10
	Median	43	41	32	175	51	15
	75th percentile	55	115	48	186	61	18
	Maximum	94	198	56	215	69	44
$(NO_2^- + NO_3^-)$–N	Minimum	4	0	6	5	4	6
	25th percentile	21	5	17	14	8	6
	Median	28	12	19	17	21	9
	75th percentile	49	15	26	24	22	27
	Maximum	69	42	27	33	26	30
TP	Minimum	23.9	16.7	21.4	18.2	20.7	11.7
	25th percentile	40.7	21.2	25.0	52.9	21.4	27.5
	Median	49.7	37.9	48.1	74.4	26.4	40.3
	75th percentile	81.0	48.8	58.0	101.0	27.2	60.1
	Maximum	171.0	66.7	58.3	125.0	43.4	75.2
TKN	Minimum	450	440	600	730	650	530
	25th percentile	800	680	700	880	720	650
	Median	1030	770	750	1170	730	1080
	75th percentile	1280	910	940	1260	770	1310
	Maximum	1800	3740	1030	1570	850	1960

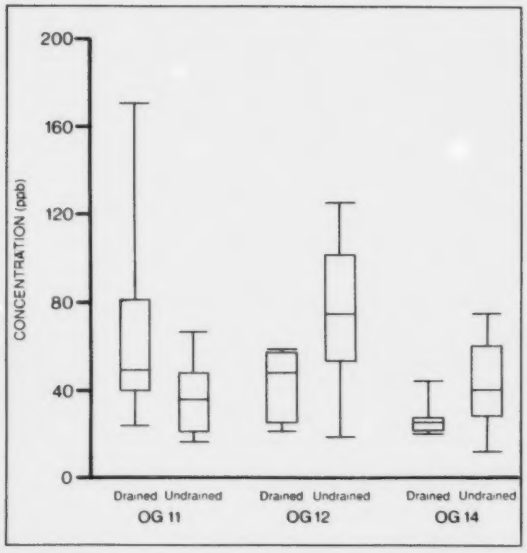

Figure 16. Total phosphorus concentrations in ground water, 1989.

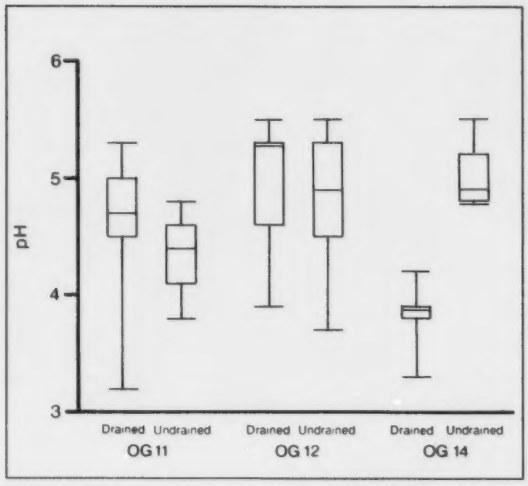

Figure 17. pH in ground water, 1989.

Table 18. Descriptive statistics for groundwater pH and conductivity — combined 1987, 1988 and 1989 data.

		Operational group (OG)					
		11	11C	12	12C	14	14C
pH	Minimum	3.2	3.8	3.9	3.7	3.3	4.8
	25th percentile	4.5	4.1	4.6	4.5	3.8	4.8
	Median	4.7	4.4	5.3	4.9	3.9	4.9
	75th percentile	5.0	4.6	5.3	5.3	3.9	5.2
	Maximum	5.3	4.8	5.5	5.5	4.2	5.5
Conductivity (µS/cm)	Minimum	30	30	50	13	18	25
	25th percentile	50	30	53	26	30	30
	Median	55	40	60	35	50	35
	75th percentile	65	45	65	35	55	35
	Maximum	75	55	70	40	65	40

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